

Does parton saturation at high density explain hadron multiplicities at LHC ?

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This note is an addendum to [1, 2]. In these papers we pointed out that charged-particle multiplicities measured in central heavy ion collisions at high energies may not *directly* be determined by the initial conditions as given by saturation models, but in addition by the way gluons are thermalized. This process may fill the gap between the multiplicities expected e.g. from saturation models with running coupling BK equation (rcBK) [3] and the ones measured by the ALICE Collaboration [4, 5] in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. We argue that this enhancement is evidence for a factor $1/\alpha_s^{2/5}$ present in the weakly-coupled process of the "bottom-up" equilibration mechanism due to nonconservation of the number of gluons, i.e. due to entropy production.

At RHIC and LHC energies in the central rapidity region of heavy ion collisions at high density energy is deposited mainly in the form of gluons. In saturation models (hereafter

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referred to SAT) [3, 6–11] it is generally assumed that the initial gluon density determines the number of produced (charged) particles, i.e. that there is a direct correspondence between the number of partons in the initial state and the number of particles in the final state.

In this note we propose a possibly more realistic description, which departs from taking the initial condition as the only one determining ingredient for the final hadronic state. This description is based on the “bottom-up” scenario [1, 2], i.e. based on the assumption of weakly-coupled processes leading to equilibration of a non-Abelian plasma.

Although the original “bottom-up” picture does not account for the physics of plasma instabilities in the early stages of thermalization [12] which completely change the stages to thermalization except for the last one, with the result that the thermalization temperature and the thermalization time are correctly given by the “bottom-up” estimate [13]. A crucial consequence is that the number of gluons is increasing between initial and equilibration times, i.e. the final multiplicities are not related to the initial condition only, but also to the way gluons are thermalized. There is entropy production [14] here dominated by the soft gluons in the final stage of thermalization [15]. In the following there is an equality assumed between the number of partons in the final state and the number of observed hadrons (“parton-hadron duality” [16]).

Under the SAT assumption the hard gluons (on the saturation scale Q_s) are conserved in number, and they finally hadronize, after passing through a hydrodynamical stage. The “bottom-up” scenario is characterized by the fact that hard gluons are degrading, soft ones are formed and start to dominate the system. The number of gluons is increasing with proper time τ , such that the ratio R as the number of soft versus hard initial gluons is parametrically estimated in terms of the gluon densities $n_{soft}(\tau)$ and $n_{hard}(\tau)$, respectively,

$$R = [n_{soft}(\tau)(Q_s\tau)]|_{\tau_{eq}} / [n_{hard}(\tau)(Q_s\tau)]|_{\tau_0} \sim \alpha_s^{-2/5}, \quad (1)$$

derived in [1].

In the following, in order to provide explicit quantitative predictions for particle multiplicities in this scenario we go as much as possible beyond the parametric estimates. As the main drawback of the model two theoretically undetermined constants c_{eq} and c have to be introduced [1], i.e. via the equilibration time

$$\tau = \tau_{eq} = c_{eq} \alpha_s^{-13/5} Q_s^{-1}, \quad (2)$$

and the equilibration temperature, which is expressed by

$$T_{max} = T_{eq} = 0.16 \, c \, c_{eq} \, \alpha_s^{2/5} (Q_s^2) \, Q_s. \quad (3)$$

In terms of these undetermined parameters one finds for the ratio R ,

$$R \simeq 0.13 \, c^2 \, c_{eq}^4 \alpha_s^{-2/5} (Q_s^2). \quad (4)$$

To be quantitative we estimate these two constants with the help of the ALICE multiplicity measurement [4] together with RHIC data at $\sqrt{s_0} = 130 \, GeV$ [17] as in [1] in order to see if plausible estimates for τ_{eq} and T_{eq} result.

The ratio $R(2.76 \, TeV)$ for the LHC energy at $\sqrt{s} = 2.76 \, TeV$ is estimated by taking the ALICE value [4]

$$dN_{ch}/d\eta = 1584 \pm 4(stat) \pm 76(sys), \quad (5)$$

and as a reference value for SAT the one from [3],

$$dN_{ch}/d\eta (2.76 \, TeV) = 1175 \pm 75, \quad (6)$$

which underpredicts the ALICE value (see FIG. 4 in [4]), as [3] relates the multiplicity directly to the CGC initial state configuration, and it solves the BK equation using the running coupling (rcBK) [11].

The underestimated value (6) may be enhanced by the interaction of gluons, which are redistributed and thermalized. Using (5) and (6) we estimate

$$R(2.76 \, TeV) \simeq 1.35 (\pm 0.15). \quad (7)$$

We take the parametrizations from [1] at $\sqrt{s_0} = 130 \, GeV$:

$$Q_s^2 = (s/s_0)^{\lambda/2} \, Q_{s_0}^2, \quad \lambda = 0.25, \quad Q_{s_0}^2 = 2 \, GeV^2, \quad \alpha_s = 0.35, \quad (8)$$

and

$$Q_s^2 (2.76) = 4.3 \, GeV^2, \quad \alpha_s = 0.3, \quad (9)$$

with $\Lambda_{QCD} = 0.2 \, GeV$.

Although there is a lot of freedom, as an illustrative numerical example we choose $R(130 \, GeV)c = 3$ as in [1] to fix the RHIC multiplicity [17]. Plausible $O(1)$ estimates for the constants follow:

$$c \simeq 2.4 (\pm 0.2), \quad c_{eq} \simeq 1.1 (\pm 0.1). \quad (10)$$

Eqs. (2) and (3) give the estimates $\tau_{eq} \simeq 2.2 \text{ fm}$ and $T_{eq} \simeq 490 \text{ MeV}$ at the LHC energy $\sqrt{s} = 2.76 \text{ TeV}$, to be reasonable values in the framework of pQCD.

For the higher energy at $\sqrt{s} = 5.5 \text{ TeV}$ we expect, using $Q_s^2 = 5.1 \text{ GeV}^2$, $\alpha_s = 0.29$, $R(5.5 \text{ TeV}) \simeq 1.38$,

$$dN_{ch}/d\eta \simeq 1910 (\pm 50), \quad (11)$$

enhancing the SAT value [3]

$$dN_{ch}/d\eta = 1390 \pm 95. \quad (12)$$

Using $N_{part} = 381$ (taken at 2.76 TeV [4]) gives

$$\frac{2}{N_{part}} dN_{ch}/d\eta \simeq 10.0, \quad (13)$$

in agreement with the ALICE fit using the proportionality $\propto s^{0.15}$ (see FIG. 3 [4]).

The dependence of $dN_{ch}/d\eta$ as a function of N_{part} found by the ALICE Collaboration (see FIG. 2 in [5]) is similar to that observed at RHIC energies [17–20] which has been shown to be consistent with the "bottom-up" expectation (see Fig. 2 in [1]).

In summary, the description for particle multiplicities provided by the "bottom-up" scenario, due to inherent entropy production, reproduces the RHIC and LHC data, provided the parameters c and c_{eq} , which are not determined in the picture, lie in a given, limited range of $O(1)$. Due to the interactions of gluons, which are redistributed and thermalized in this kinetic scenario, the initial gluon spectrum is strongly modified, i.e. enhanced.

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